ROBOTICS AND INTELLIGENT MACHINES: A DOE CRITICAL TECHNOLOGY ROADMAP

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ABSTRACT – The Robotics and Intelligent Machines (RIM) Roadmap is a US Department of Energy (DOE)-wide, high-level, strategic "critical technology" roadmap requested by the Office of the Under Secretary of Energy in 1998. The RIM roadmap resulted from a determination by DOE management to develop technology roadmaps for its major programs with a renewed concentration on needs-driven science and research and development (R&D). An additional driver was an expressed desire by Congress for increased emphasis and integration in RIM R&D within 5 government agencies to take advantage of new innovations and to improve US international competitiveness. The RIM roadmap was developed by a core team representing 9 Principle Secretarial Offices (PSO) within DOE with assistance from representatives from DOE National Laboratories, DOE sites and other Federal Agencies. The resulting RIM roadmap is a high-level strategic document created to establish a credible, common long-term vision for RIM with Congress, DOE Management, private industry, academia, researchers, and users. The purpose of the RIM roadmap is to identify, select, and develop objectives that will satisfy near- and long-term challenges posed by DOE's mission objectives. Development of the RIM roadmap began with definition of major needs of each of the participating PSOs over the next several decades. From these needs, functional objectives were identified in which advances in RIM technologies could play a major role in enabling each PSO to meet its goals. Each functional objective includes a metric with specific values for the metric associated with time frames termed Epochs in the RIM roadmap. Epoch I ends in year 2004, Epoch II in year 2012, and Epoch III in year 2020. After identifying the set of functional objectives, 4 underlying basis technology areas were determined within which individual RIM technologies relevant to each functional objective could be defined. A chart was developed for each functional objective that identified the technologies required to realize that functional objective. The technologies and the applications that will utilize those technologies are identified within each Epoch providing a time phased technology development plan to meet the metric established for each functional objective during each Epoch. Research and development in RIM, as defined by the RIM roadmap, coupled with advances in computing, communications, electronics, and micro-engineering, will provide DOE with a dramatically new set of tools which will change the way DOE accomplishes its missions. This paper describes the drivers and processes used to develop the RIM roadmap, benefits derived from the results of the roadmap, and lessons learned from the road mapping exercise.

INTRODUCTION

The Robotics and Intelligent Machines (RIM) Roadmap is a US Department of Energy (DOE)-wide, high-level, strategic "critical technology" roadmap requested by the Office of the Undersecretary of Energy in 1998. The RIM roadmap was developed by a core team representing 9 Principle Secretarial Offices (PSO) within DOE with assistance from representatives from DOE National Laboratories, DOE sites and other Federal Agencies. This paper describes the drivers behind the creation of the RIM roadmap; the philosophies, processes, and resources used in developing the roadmap; key products produced within and associated with the roadmap; benefits derived from the results of the roadmap; and lessons learned from the roadmapping experience. The RIM roadmap was developed as a DOE-wide roadmap across multiple PSOs. The general process is described as applied to the efforts across all PSOs, however, for this paper emphasis is given to the portions of the roadmap effort associated with the Office of Environmental Management (EM). Therefore, specific details and examples are drawn from the EM portions of the RIM roadmap.

DRIVERS FOR A RIM ROADMAP

The Robotics and Intelligent Machines (RIM) Roadmap [1] had its genesis as the result of two coinciding determinations. The first was finalization of the DOE Strategic Plan [2] and subsequent determination by DOE management to develop technology roadmaps for its major programs with a renewed concentration on needs-driven science, research, and development. The second was an expressed desire by Congress for increased emphasis and integration in RIM R&D within 5 government agencies to take advantage of new innovations and improve US international competitiveness. The convergence of these two ideas led DOE leaders to conclude that RIM was an “enabling technology” critical for the success of DOE missions; and, therefore, warranted a Department-wide analysis at the level of it’s major programs.

Because of the breadth of the RIM initiative, it is imperative that there be awareness and use of the R&D conducted in other agencies when appropriate. To this end, in 1995, a MOU was signed between the Robotic Industries Association and the IEEE Robotics and Automation Society with the express intent of integrating needs for robotics with the related R&D. A committee – the Robotics and Intelligent Machines Cooperative Council (RIMCC) – was formed to carry out the intent of the MOU, and has representatives from industry, academia, and the Federal agencies. This group is chaired by a technical manager from Sandia National Laboratories, and continues to provide a broad IEEE-based forum for integration. In addition to the RIMCC, there is already significant cross-fertilization of activities. As examples, the DoD is using DOE technologies as it explores the demilitarization of it millions of tons of conventional munitions. And DOE laboratories are supporting DARPA with mobile robot technology as it carries out R&D for the future battlefield. There are additional interactions with the DoD as well as NASA, NIST, and NSF.

The September 1997 DOE Strategic Plan identified four business areas (National Security, Environmental Quality, Science Leadership, and Energy) that use and integrate DOE’s unique scientific and technological assets, engineering expertise, and facilities for the benefit of the Nation. Each of these business areas are supported by multiple Principal Secretarial Officers (PSOs).

Many of these Offices currently support R&D for use in RIM-related applications such as manufacturing, dismantlement, materials handling and monitoring, facilities remediation, characterization, and stabilization. Therefore, the Secretary decided that RIM was a “Critical Technology” which crosscut activities in almost every PSO, business, and mission area.

In November, 1997, a letter [3] from the Senate Task Force on Manufacturing was signed by Senators Lieberman, Snowe, Bingaman, Domenici, and D’Amato, along with Congressmen Franks and Meehan. The letter was sent to the Secretaries of Defense, Energy, and Commerce, the Administrator of NASA, and the Director of the National Science Foundation endorsing an eight point program to advance the state-of-the-art in robotics and intelligent machines. (Robotics and Intelligent Machines Roadmap Executive Summary October 1998).

RIM technology is coming of age now, at the beginning of the 21st Century. In large part this is because advances in the fundamental technologies that underlie RIM have also come into their own. For example, computing speed, increasing as predicted by Moore’s law, has been doubling every 18-24 months and is becoming able to accommodate the algorithms and software associated with RIM’s “intelligence.”. One A particularly important indicator for the long term is “Moore’s Law,” which predicts the availability of more than a thousand fold increase in computing speed by the year 2020 (the horizon of this roadmap). Ongoing revolutions in computing, communication, electronics, and microengineering will enable the development of these new capabilities. Among these, the following are considered significant:

- Microsensors, applicable to a variety of physical phenomena, suitable for major challenges in RIM perception systems;
- Emerging capabilities for integration of complex systems; and
- Expanding collaboration among engineers and scientists facilitated by the Internet.

The science and technology program of the RIM Initiative involves research development and deployment of systems composed of machines, computers, sensors, and system "intelligence" codified in the form of mathematics, physics, computer and information science, rules and computational models. Together, these components provide the flexibility, adaptability and intelligence that are making the new RIM systems viable solutions to some of DOE's most intractable problems. Underscoring this point, mounting evidence from systems currently in operation within DOE provide evidence that modern software engineering processes and reliable microcomputer and communication technologies are enabling machines to make decisions based on algorithms and sensed information without endangering the safety of the operations in which they are engaged. Indeed, in many cases operational safety is being improved.

It was with this new context, therefore, that the Secretary and Undersecretary Ernie Moniz decided to charter a "critical technology" roadmap for RIM.

ACCOMPLISHING THE RIM ROADMAP

A "Core Team" of representatives from the PSO's and from 3 DOE National Laboratories (Sandia, Oak Ridge, and Idaho) developed the RIM Roadmap. The DP representative served as chair. The Lab representatives were assigned specific PSO's to support. The Core Team received its charge and direction from a representative of the Office of the Under Secretary. The guiding principles to the Core Team from the Under Secretary included the following:

- Stay Focused on DOE and End-User Needs.
- Reduce Programmatic Risk-Bridge the Gap Between S&T Activities and Technology Deployment.
- Make Use of Ongoing Work in Industry and Academia.
- Coordinate and Integrate Activities Among DOE Offices and the National Labs

This representative maintained constant and very active two-way communication between the Under Secretary and the Core Team throughout the road mapping effort and participated in many of the Core Team meetings. The Core Team also depended on the support of a wide variety of individuals for input, advice, and counsel. Table 1 lists the entire RIM Roadmap Development Team which was quite disparate in its makeup(e.g. scientists, engineers, program managers, facility managers, PhDs, non-degreed, lab people, field people HQ people, etc). Sandia took the lead for facilitating the roadmap generation and publishing effort and engaged the services of McNeil Technologies for that end. The PSO's listed below, provided long-range strategic or other plans to the Road mapping Team. These plans served as a starting point for the Team to ensure that the Roadmap was grounded in DOE's needs. Specifically, EM used the *Paths to Closure* [4] document as well as Multi-Year Program Plans. DOE Offices, sites and laboratories contributing plans and guidance to the road mapping effort included:

- DOE Core Group
  - Defense Programs (DP), Chair
  - Fissile Materials Disposition (MD)
  - Environmental Management (EM)

  - Nuclear Energy Science and Technology (NE)
  - Science (SC)
  - Nonproliferation and National Security (NN)
  - Environment Safety and Health (EH)
  - Energy Efficiency and Renewable Energy (EE)
  - Fossil Energy (FE)

- National Laboratory Support Group
  - Sandia National Laboratories, Chair
  - Oak Ridge National Laboratory
  - Idaho National Environmental Engineering Laboratory
  - Los Alamos National Laboratory
  - Lawrence Livermore National Laboratory

- DOE Site Support Group
  - Pantex
  - Allied Signal FM&T
  - Lockheed Martin Y-12 Plant
  - Savannhah River Technology Center

- Other Federal Agencies

  - National Science Foundation
  - Defense Advanced Research Projects Agency

The Core Team developed the Roadmap document essentially between January and July of 1998. The Team would meet at least monthly in DC to deliver it's scheduled input, discuss that input, receive directions on the next assignment, go through an exercise in developing that assignment, provide feedback on the exercise, and agree to the next assignment details, schedule and meeting dates. During the next interim, the individual PSO teams would prepare the assigned tasks in preparation for the next meeting. EM turned to its existing Focus Area/Crosscutting structure to complete its assignments. The Robotics Crosscutting Program (Rbx) Product Line Managers (PLM) worked with their respective Focus Area to generate the raw input for the EM reps on the Team. It would have been infeasible for them to canvas every, or even selected users at EM sites given the expedited schedule. At one stage, the DOE Mixed Waste Focus Area Lead and an SRS Facility Manager were brought in to validate the in-progress results of this approach. During the interim between Core Team meetings, the EM Team and Core Team made extensive use of e-mail and file exchanges, straw man papers, and overnight mailings. The EM Team also met during that time at Albuquerque or Germantown, depending on need. There were also periodic, formal presentations to the DOE R&D Council by the Core Team.

The Core Team first had to decide at what level the roadmap would be targeted. Given the drivers for the roadmap explained above, it was concluded the roadmap had to be a high-level strategic document to establish a credible, common long-term vision for RIM with Congress, DOE Management, private industry, academia, researchers, and users. During this first step, it was agreed that fine technical detailing would be limited value. Also, technical detailing could stifle progress, therefore, , "80% was good enough". Nonetheless, given the complexity of the EM scope, the EM team consciously strove to maintain a "frame-of-reference" meaningful to the Focus Areas and ultimate user to facilitate their support in continuing efforts. The Core Team realized there would be many such competing points of view and, therefore, agreement was reached in the first meeting that the overall effort was more important to the DOE-wide stakeholders than any individual difference. Consequently, "logos would be left at the door" for PSO's and Labs alike.

Although the direction from DOE management was that the DOE Roadmap would deal with DOE scope only, the Core Team kept in mind that the effort could eventually expand to or would later be integrated across multiple agencies to satisfy Congress. Representatives from those agencies were invited to attend Core Team meetings and a separate meeting was held with those agencies just to reach mutual understanding of the DOE effort and the efforts of the other agencies. These exchanges proved the true crosscutting nature of RIM. The process the Core Team used is reflected in Figure 1 showing the structure of the RIM roadmap.

Robotics and Intelligent Machines Technology Roadmap
From Needs to Science and Technology

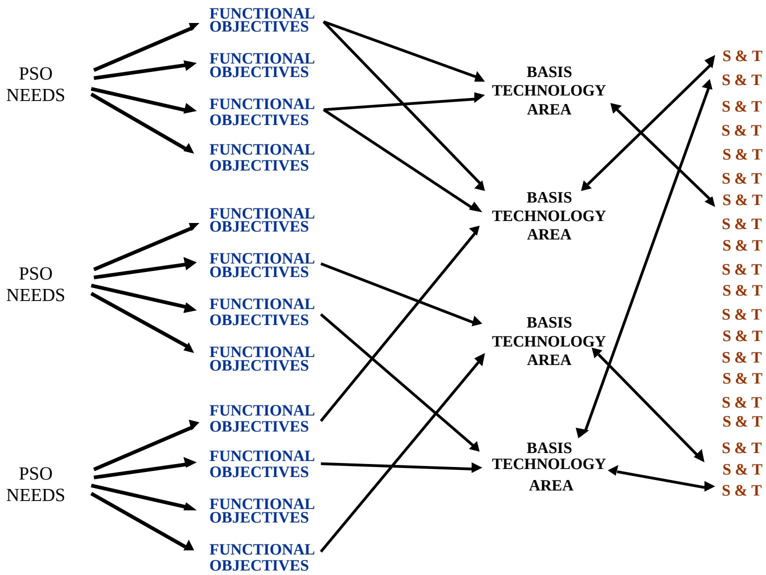


Figure 1, RIM Roadmap Hierarchy

Starting from the left, the Core Team began with the individual and diverse business needs of the PSOs. From these, the Team developed a description of the Functional Objectives and potential applications for RIM. The Functional Objectives (see Table 1) essentially provide the PSO justification for using RIM technologies to satisfy their needs. As seen in the Table 1, a total of 23 Functional Objectives were identified.

Several crosscutting themes are evident in the complete list of Functional Objectives. Among these are

- **Reduced cost.** The capabilities of RIM have the potential to advance so rapidly that initial capital costs of the systems will be easily compensated for by a decrease in operating costs. This will assist DOE to meet its obligations in the face of inflation and other budgetary pressures.

- **Improved Worker health and safety.** DOE intends to remove workers from the dangers of radioactive, explosive, toxic, and other hazardous materials. RIM is an obvious, and in some instances the only means to accomplish this.

PSO	FUNCTIONAL OBJECTIVES
Defense Programs	· Time and cost for refurbishment of appropriate stockpile hardware reduced by 50% · Worker exposure to hazards to 30% of current · Production defects reduced by 90%
Fissile Materials Disposition	· 75% reduction in exposure · 50% increase in operational throughput · 75% reduction in monitoring cost *These are examples. There are goals specific to different MD facilities.*
Nuclear Energy, Science and Technology	· Enable extreme environment operations/reduce risk at Chornobyl · Improve DOE reactor and commercial reactor operation · Reduce exposure (75%) and costs (50%) associated with maintenance of depleted UF_6 cylinders in storage
Nonproliferation and National Security	· Improve surveillance, accountability, and protection of domestic and international weapons-grade nuclear material
Environmental Management	· Personnel exposure reduced by 99% · Secondary waste reduced by 90% · Productivity increased by 300%
Science	· Inherently distributed missions in dynamic, uncertain environments · Sensor integration for distributed robot systems · Revolutionary collaborative research using remote and virtual systems · Intelligent machines concepts and controls methodologies for manipulative tasks · Predict safe life of welded structures · Energy resources exploration and ecological land control · Improved operation of SC strategic facilities to meet programmatic needs
Energy Efficiency and Renewable Energy	· Diffusion of manufacturing technology for renewable energy equipment · Diffusion of intelligent processes for resource efficiency/reduction of waste
Fossil Energy	· Technology diffusion, e.g., technologies for safety and productivity in extreme environments
Environment, Safety, and Health	· Improved worker health and safety

Table 1. PSOs and Functional Objectives

- **Improved Product quality.** RIM provides DOE with the opportunity and the capability to eliminate many design- and production-related defects.

- **Increased productivity.** While the remote systems of the past were characterized by slow, painstaking operations required to ensure safety, emerging RIM will offer improved safety while increasing efficiency and enabling much higher facility throughput.

As an example of how each PSO maintained its unique point of view and how flexibility to change is needed, the EM team considered “increased productivity” to include reduced cost and improved product quality. It should also be pointed out that the road mapping effort was being conducted at the same time the EM R&D Program Plan [5] was being issued. The three EM functional objectives shown in the table turned out to be very consistent with that plan with the exception of an objective that was later adopted by the EM RIM team from the EM R&D plan. That fourth functional objective is:

- **Reduced technical risk.** This is the programmatic risk (as opposed to the risk to the environment or the safety and health of workers) that critical cleanup projects may not be completed on time and/or budget due to a technology deficiency. RIM provides systems to accomplish tasks not previously possible, provides more information (characterization) to support better decisions, and provides contingency alternatives when others may involve uncertainty.

The Team then had to agree on just what defined RIM or what could represent a model/construct for RIM. The four "basis" areas described below resulted from this exercise.

- **Perception Science and Technology.** Perception systems provide a means for RIM to gather information about the working environment—information that permits operations such as manufacturing, processing, navigation, monitoring and manipulation to be accomplished safely and precisely. Recent developments in sensor technologies promise a new generation of devices that are more sensitive, more accurate, and more efficient, extending the realm of perception to a broader range of phenomena.

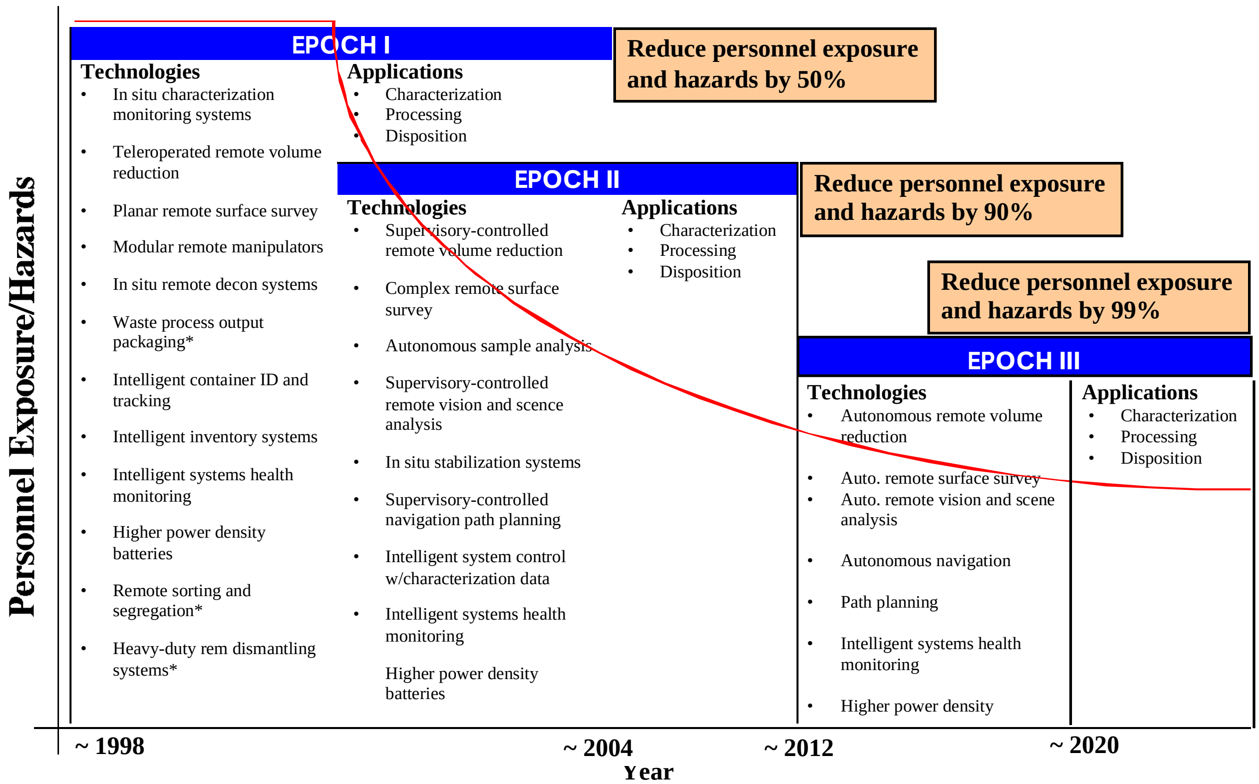
- **Reasoning Science and Technology.** Reasoning is the "smarts" of an intelligent machine, providing it with the ability to form the complex connection between perception and action. Without reasoning, machines are relegated to perform static, repetitive actions that do not respond or adapt to a changing environment. The DOE needs for RIM will require them to make intelligent and safe decisions on their own without explicit guidance from humans.

- **Action Science and Technology.** The ability to move and manipulate objects of varying forms and hazards in space is a key capability of RIM. Such devices and tools will include grasping systems and tactile hands, sensors, inspection and vision systems, and cutting, digging, surface removal and coating tools. General requirements for the robotic machines of the future include accommodating task-appropriate payloads, levels of precision, speed and dexterity.

- **Novel Interfaces and Integration Systems.** Intuitive human-computer-machine interfaces for RIM do not yet exist. The integrated systems of the future will offer interfaces that are as intuitive as the best of today's personal computers, and applications programs that are easy to bring quickly into a state of safe and reliable operation.

Next, the Team identified and described the individual sciences and technologies (S&T) needed to support each of the basis areas. By combining its understanding of the PSO needs with its knowledge of the basis technology areas, the Team was able to establish the evolution of technologies needed to meet DOE RIM needs through 2020. The twenty years were divided into three "epochs" to reflect the evolution of R&D to meet near-term and finally, long-term needs with interim functional goals. Figure 2 shows how all this information was summarized for one of the EM Functional Objectives. Near-term needs were considered "market pull"; where as, long-term needs were considered "technology push". In the resulting one document, the DOE-wide technology roadmap for RIM will provide the complete *line of sight* between the needs of DOE businesses and the requisite associated technology development

EM Driver: Reduce Personnel Exposure and Hazards



*Indicates that technology evolves through teleoperated (E1), supervisory controlled (E2), and autonomous (E3). (Due to space limitations, not all technologies could be listed on the above slide.)

Figure 2, Functional Objective Chart

KEY PRODUCTS

The key products from the RIM roadmap exercise are:

- The RIM Roadmap
- The RIM First Biennial Program Plan
- The RIM Management Plan

The RIM roadmap is a high-level strategic document created to establish a credible, common long-term vision for RIM with Congress, DOE Management, private industry, academia, researchers, and users. A primary output from the RIM roadmap exercise was the definition of functional objectives by each participating PSO. Advances in RIM technologies associated with these functional objectives will play a major role in enabling each PSO to meet its goals. Table 1 presents the functional objectives identified by each PSO.

Each functional objective includes a metric with specific values for the metric associated with time frames termed Epochs in the RIM roadmap. Epoch I ends in year 2004, Epoch II in year 2012, and Epoch III in year 2020. A chart was developed for each functional objective that identified the technologies required to realize that functional objective. The technologies and the applications that will utilize those technologies are identified within each Epoch providing a time phased technology development plan to meet the metric established for each functional objective during each Epoch. The Functional Objective Charts are the key product generated during the RIM Roadmap exercise. Figure 2 provides an example of a Functional Objective Chart for one of the EM functional objectives.

The RIM First Biennial Program Plan [6] describes an integrated R&D plan for RIM technologies spanning fiscal year (FY) 2001 through FY 2005. The RIM Program Plan recognizes the maturity progression of R&D and defines four R&D stages (similar to the EM Gate/Stage definitions): fundamental research, applied research, prototype development, and development. This allows R&D to be viewed in terms of both time and stage where fundamental or applied research funded in early FYs results in, or contributes to, applied research, prototype development, and development projects in subsequent years that meet the Functional Objectives identified in the RIM Roadmap. Figure 3 illustrates this process.

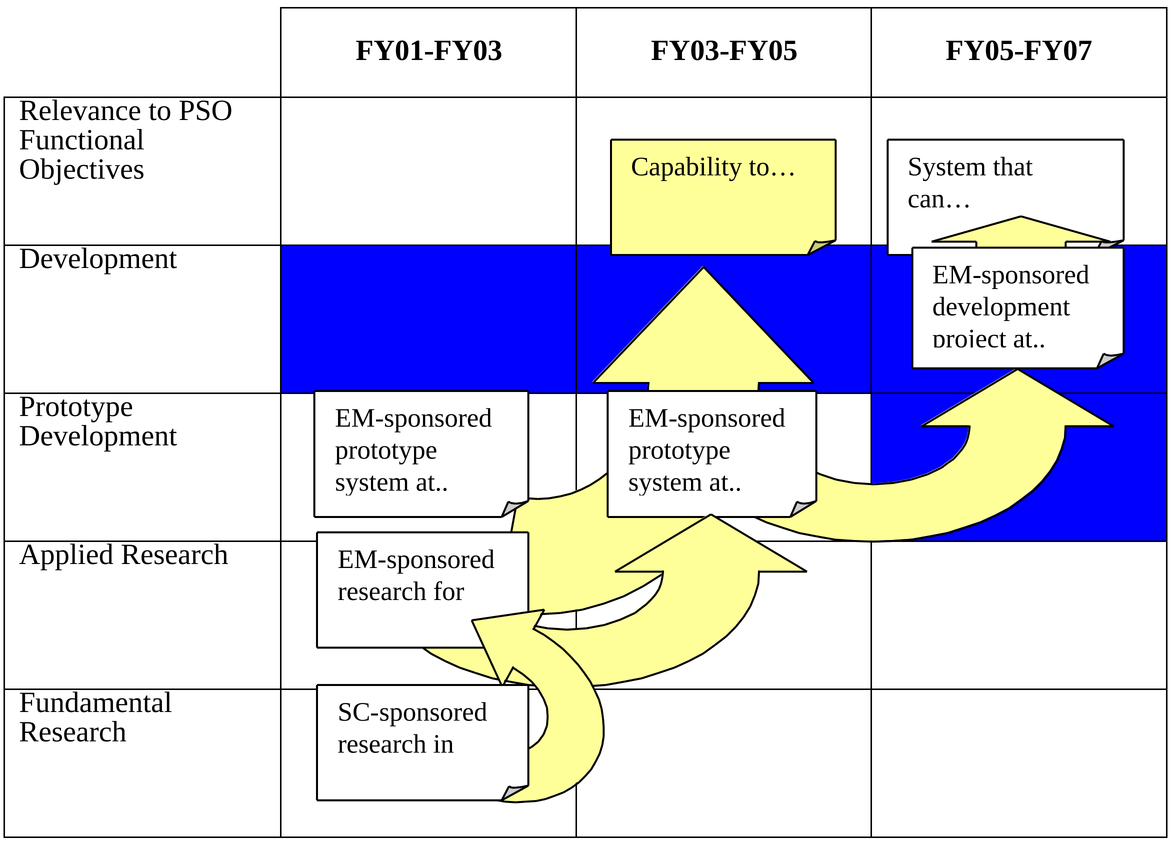


Figure 3. The RIM Program Plan Maps R&D by Fiscal Year and Stage of R&D

The key product of the RIM Program Plan is the definition of Research Areas that identify specific research topics of immediate interest. These Research Areas provide the basis for calls for R&D projects within each PSO and provide opportunities for cross-PSO collaboration and leveraging. Table 2 presents the Research Areas for the Office of Science, Defense Programs, and EM. The RIM Program Plan provides more detailed discussion of each of these Research Areas.

OFFICE OF SCIENCE RESEARCH AREAS
▪ Cooperating Robots in Dynamic Uncertain Environments ▪ Advanced Multisensor Science and Technology ▪ Intelligent Machines Concepts and Control Methodologies ▪ Remote and Virtual RIM Systems ▪ Energy Resources and Ecology Monitoring by Robotic Systems ▪ Exploration of Intelligent Machines for Industrial Purposes
DEFENSE PROGRAMS RESEARCH AREAS
▪ Intelligent Inspection and Processing ▪ Smart Fixturing ▪ Direct and Micromanufacturing ▪ Monitoring, Security and Material Movement Robots ▪ Emergency Response Mobile Robot ▪ Cooperative Assists
OFFICE OF ENVIRONMENTAL MANAGEMENT RESEARCH AREAS
▪ Advanced Remote Handling ▪ Advanced Waste and Task Environment Characterization ▪ Remote Work System Mobility ▪ Task-Driven Computer-Aided Engineering ▪ Remote Operator-Machine Interface/Cooperation ▪ Remote Operations Simulation and Training

Table 2. RIM Program Plan Research Areas

The RIM Management Plan [7] was produced to establish a process for management and integration of RIM activities across PSOs. The Management Plan established a RIM Core Management Group reporting to the R&D Council. The purpose of the Core Management Group is to integrate the selection, planning, and funding of RIM-related projects throughout DOE.

BENEFITS OF THE RIM ROADMAP

It has been interesting to note how the resulting new RIM vision and discussions of even conceptual projects has impacted new requests for proposal calls for EMSP and Applied Research. In addition, RIM-related language is becoming part and parcel of EM Program documents like the EQ Portfolio, EQ Portfolio gap analysis [9], and proposed revisions to the EM R&D Program Plan [10]. RIM is becoming part of the EM institution.

The DOE RIM Roadmap identifies a path forward for the department as it focuses RIM type development to support its missions and simultaneously advance RIM state-of-the-art. The RIM Roadmap presents for Environmental Management (EM) an opportunity to identify R&D that is grounded in its customer's technology needs while striving to meet objectives that will reduce personnel exposure and hazards, reduce secondary waste, and increase productivity. These three *functional* objectives are common threads that link EM R&D projects to the RIM Roadmap. Accordingly, the roadmap provides a structured tool with a common language for stakeholders like the Focus Areas to develop a meaningful program and to allocate resources responsibly.

EM Perspective

Over the last few years EM has refined its focus of the DOE weapons complex cleanup. This refinement emphasizes near-term deployment of innovative technologies that address the near-term needs of the end-user. Coupled with government wide budgetary constraints, this technology development approach has left little to no room for early R&D in the area of RIM. Moreover, EM's current research portfolio in this area does not significantly further or impact the United States' technological position in RIM development. The roadmap has been useful in identifying the funding gap and needs for early R&D. It is therefore referenced in the new EQ Portfolio Gap Analysis.

EM Current RIM Approach

EM's approach to R&D in robotics has been primarily through its Robotics Crosscutting Program (Rbx). The program is responsible for the development of robotic and remote systems that meet the near-term needs that its Focus Area customers have identified. RIM technology development addressing near-term needs currently falls under four focus areas:

- Tanks Focus Area
- Mixed Waste Focus Area
- Deactivation and Decommissioning Focus Area
- Nuclear Material Focus Area.

On the other hand, there were hurdles that the roadmap encountered or could not overcome. Support from DOE mid-level managers was significantly tempered by the concern that RIM would have to be funded from their already limited resources. Unfortunately, this also may have been the weakest link in the communication efforts. Crossing the stovepipes into other government agencies proved to be a much more challenging effort requiring a higher level of coordination than originally anticipated. In the end, not all the PSO's participated with the same level of interest as the primary players, or had the wrong representatives assigned. Some insisted that their limited RIM needs did not warrant greater participation. After all the effort to represent a DOE-wide picture, some PSO's have subsequently issued their own roadmaps with substantial RIM technologies included. And, finally, the effort required a significant amount of travel which probably couldn't be accomplished under current restrictions.

LESSONS LEARNED

The road mapping exercise was a powerful experience for all that participated. Common goals and objectives were realized while dealing with a very complex challenge and utilizing organizations/individuals that often compete with one another. Listed below are the key lessons learned during the process.

Focus

Early, very clear guidance/principles from the sponsor/advocate will continue to serve as touchstones throughout the effort to keep it on track. A needs focus and defined functional objectives (requirements) will keep the roadmap grounded and credible. Also will become vital part of project selection process when roadmap is implemented.

Advocacy

This effort had a clear, high-level sponsor in the Undersecretary. Communications with him were essentially direct and very frequent. This kept the effort in line with up-to-date expectations that were passed on to all participants

Leadership

This effort had well-defined leadership who took responsibilities seriously and was proactive at every step. The Sandia/McNeil Technologies team that coordinated the process, planned every step, yet was flexible to opportunities, kept the team focused and productively on task, the critical guidelines and rules were established immediately that made the difference over and over during the effort ("80% is good enough" and "leave the logos at the door" standout). This team kept communications flowing at an impressive pace. They set intermediate deadlines then held everyone's feet to the fire to meet them.

Communications

Not only are communications with the sponsor important but with all participants, which in this case were spread all over the country and who had such apparently disparate "frames of reference" and motivations. Every mode imaginable was brought in to play, meetings in DC, meetings in airports, e-mails, overnight delivery, pagers, cell phones, intermediaries, etc. The electronic traffic alone mandated that everyone be on the same version of software. As was stated before, probably not enough effort was spent communicating with the mid-level managers at DOE. Another aspect of effective communications is taking measures to assure such a disparate team is truly using common terminology. This led to defining the four basis areas that are now proving a powerful tool in communicating to others what RIM really is. Another example was what became nicknamed as the "Rosetta Stone". Shown in Figure 3, the Rosetta stone was a device to translate between different PSO models of the R&D maturity cycle.

Defining and keeping roadmap in the frame of reference of the target audience will assure roadmap will be effective in the long-term. It is also important to keep in mind that the target audience shifts as the roadmap is implemented so all the seeds have to be planted in the genesis document.

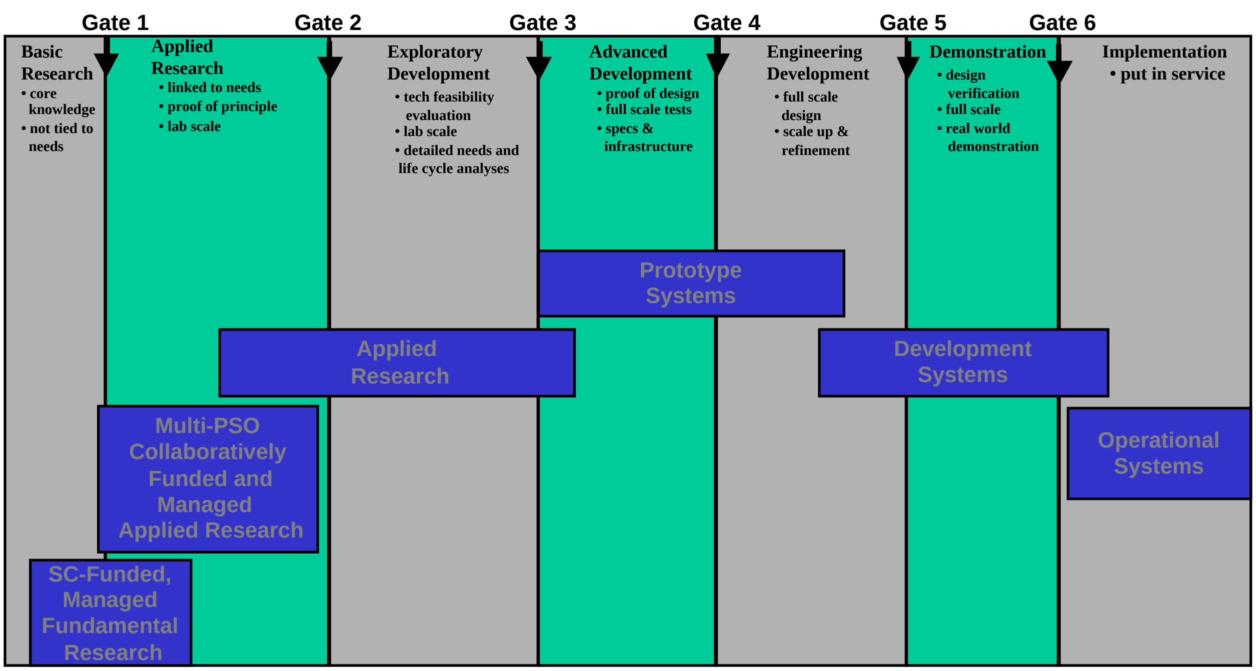


Figure 3, Rosetta Stone: Mapping RIM Program Elements on to the EM Gate Structure

SUMMARY

The RIM Roadmap was successfully developed in 1998 through the hard work and cooperation of a diverse team of scientists, engineers, program managers, facility managers, PhDs, non-degreed staff, laboratory staff, field operations staff, and DOE headquarters staff. The resulting roadmap met the needs of DOE management for a DOE-wide critical technology roadmap for robotics and defines a long-term technology development plan which addresses the congressional request for increased emphasis in RIM R&D. The RIM Roadmap and associated documents define a technology development R&D program that spans the spectrum from fundamental research to field systems, all tied to specific DOE functional objectives. Research and development in RIM, as defined by the RIM roadmap, coupled with advances in computing, communications, electronics, and micro-engineering, will provide DOE with a dramatically new set of tools which will change the way DOE accomplishes its missions.

ACKNOWLEDGEMENTS

In this paper, the authors are summarizing the results of the overall RIMRoadmap effort. This was an effort involving the teamwork of colleagues at multiple locations across the DOE complex and other federal agencies. In particular, it is appropriate to acknowledge the leadership and coordination that was provided by Dr. Patrick Eicker of the Sandia National Laboratories.

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